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COMPARATIVE STUDY OF PERFORMANCE, COMBUSTION AND EXHAUST EMISSIONS ANALYSIS OF LINSEED OIL BASED BIODIESEL IN A CERAMIC COATED DIESEL ENGINE

S. NARASIMHA KUMAR

Department of Mechanical Engineering, Chaitanya Bharathi Institute of Technology, Hyderabad, Karnataka, India

ABSTRACT

The uses of biodiesel are increasingly popular because of their low impact on environment. However, it causes combustion problems in conventional diesel engine [CE]. Hence it is proposed to use the biodiesel in low heat rejection (LHR) diesel engines with its significance characteristics of higher operating temperature, maximum heat release, and ability to handle the lower calorific value (CV) fuel etc,. In this work, biodiesel from linseed was used as sole fuel in both versions of the combustion chamber. Engine with LHR combustion chamber was developed with ceramic coating on inside portion of cylinder head by partially stabilized zirconia of 0.5 mm thickness. The experimental investigations were carried out on a four stroke, single cylinder, DI, 3,68 kW at a speed of 1500 rpm, In this investigation, comparative studies on performance parameters was made on CE and engine with LHR combustion chamber with different operating conditions of biodiesel with varied injector opening pressure and injection timing. CE showed compatible performance while LHR combustion chamber showed improved performance with biodiesel operation in comparison with pure diesel operation on CE.

KEYWORDS: Alternate Fuels, Vegetable Oils, Biodiesel, LHR Combustion Chamber, Performance Parameters

INTRODUCTION

The paper is divided into i) Introduction, ii) Materials and Methods, iii) Results and Discussions, iv) Conclusions, Future scope of work, v) Acknowledgements followed by References.

Introduction deals with investigations carried out by researchers in the work related to the authors or brief literature review. .

This section deals with need for alternate fuels in diesel engine, problems with use of crude vegetable oil in diesel engine, advantages of use of preheated vegetable oil in diesel engine, use of biodiesel in diesel engine, effect of increase of injector opening pressure and advanced injection timing on the performance of the diesel engine, concept of engine with LHR combustion chamber, advantages of LHR combustion chamber, classification of engines with LHR combustion chamber, use of diesel, crude vegetable oil and biodiesel in engine with LHR combustion chamber, research gaps and objectives of the investigations.

The world is presently confronted with the twin crises of fossil fuel depletion and environmental degradation. The fuels of bio origin can provide a feasible solution of this worldwide petroleum crisis (1-2).

It has been found that the vegetable oils are promising substitute, because of their properties are similar to those of diesel fuel and they are renewable and can be easily produced. Rudolph Diesel, the inventor of the diesel engine that bears his name, experimented with fuels ranging from powdered coal to peanut oil. Several researchers [3-6] experimented the use of vegetable oils as fuel on diesel engine and reported that the performance was poor, citing the problems of high viscosity, low volatility and their polyunsaturated character.

Viscosity can be reduced with preheating. Experiments were conducted [7-10] on preheated vegetable [temperature at which viscosity of the vegetable oils were matched to that of diesel fuel] oils and it was reported that preheated vegetable oils improved the performance marginally. The problems of crude vegetable oils can be solved, if these oils are chemically modified to bio-diesel.

Bio-diesels derived from vegetable oils present a very promising alternative to diesel fuel since biodiesels have numerous advantages compared to fossil fuels as they are renewable, biodegradable, provide energy security and foreign exchange savings besides addressing environmental concerns and socio-economic issues. Experiments were carried out [11-15] with bio-diesel on direct injection diesel engine and it was reported that performance was compatible with pure diesel operation on conventional engine.

Few investigators [16-19] reported that injector opening pressure has a significance effect [20] on the performance and formation of pollutants inside the direct injection diesel engine combustion. The other important engine variable to improve the performance of the engine is injection timing. Investigations were carried out [21-24] on single cylinder water cooled vertical diesel engine with brake power 3.68 kW at a speed of 1500 rpm with varied injection timing from 27-34^{o}bTDC. It was reported from their investigations that performance of the engine improved with advanced injection timing. However, it increased NOx emissions and decreased smoke levels.

Sound levels determine the phenomena of combustion in engine whether the performance was improving or deteriorating. Studies were made [22-24] on sound levels with convention engine with vegetable oils and it was reported from the studies, that performance deteriorated with vegetable oil operation on conventional engine leading to produce high sound levels. The drawbacks associated with biodiesel for use in diesel engine call for low heat rejection (LHR) combustion chamber.

The concept of LHR combustion chamber is to reduce heat loss to coolant by providing thermal insulation in the path of heat flow to the coolant. LHR combustion chambers are classified depending on degree of insulation such as low grade, medium grade and high grade insulated combustion chamber. Several methods adopted for achieving low grade LHR combustion chamber are using ceramic coatings on piston, liner and cylinder head. Medium grade LHR combustion chamber provide an air gap in the piston and other components with low-thermal conductivity materials like superni, cast iron and mild steel etc. High grade LHR combustion chamber contain ceramic coatings on engine components and air gap insulated components.

LHR combustion chamber with ceramic coating of thickness in the range of 500 microns on the engine components with pure diesel operation [25-27] provided adequate insulation and improved brake specific fuel consumption (BSFC) in the range of 5-7%. The investigations on low grade LHR combustion chamber consisting of ceramic coating on cylinder head were extended to crude vegetable oil [28-29] and biodiesel [30]. It was revealed from their investigations that

ceramic coated LHR combustion chamber marginally improved brake thermal efficiency, decreased smoke levels by 30% and increased NOx levels by 40%.

Little literature was available on comparative studies of conventional diesel engine and ceramic coated LHR combustion chamber with different operating conditions of the biodiesel with varied injection timing and injector opening pressure. Hence it was attempted here to determine performance parameters with linseed oil based biodiesel with CE and LHR combustion chamber with varied injector opening pressure and injection timing.

MATERIALS AND METHODS

This section contains fabrication of engine with LHR combustion chamber, preparation of biodiesel, properties of biodiesel, description of the schematic diagram of experimental set up, specifications of experimental engine, specifications of sound analyzer and definitions of used values.

The inner side portion of cylinder head was coated with partially stabilized zirconium (PSZ) of thickness of 500 microns in order to convert conventional diesel engine to low heat rejection (LHR) combustion chamber.

The chemical conversion of esterification reduced viscosity four fold. Linseed oil contains up to 72.9 % (wt.) free fatty acids [32].The methyl ester was produced by chemically reacting the linseed oil with an alcohol (methyl), in the presence of a catalyst (KOH). A two-stage process was used for the esterification [33-35] of the waste fried vegetable oil. The first stage (acid-catalyzed) of the process is to reduce the free fatty acids (FFA) content in linseed oil by esterification with methanol (99% pure) and acid catalyst (sulfuric acid-98% pure) in one hour time of reaction at 55°C. In the second stage (alkali-catalyzed), the triglyceride portion of the linseed oil reacts with methanol and base catalyst (sodium hydroxide-99% pure), in one hour time of reaction at 65°C, to form methyl ester and glycerol. To remove un-reacted methoxide present in raw methyl ester, it is purified by the process of water washing with air-bubbling. The methyl ester (or biodiesel) produced from linseed oil was known as linseed oil biodiesel (LSOBD). The physic-chemical properties of the crue linseed oil and biodiesel in comparison to ASTM biodiesel standards are presented in Table 1,

Table 1: Properties of Test Fuels

Property	Units	Diesel	Biodiesel	ASTM D 6751-02
Carbon chain	--	C_8-C_{28}	C_{16}-C_{24}	C_{12}-C_{22}
Cetane Number		55	55	48-70
Density	gm/cc	0.84	0.87	0.87-0.89
Bulk modulus @ 20Mpa	Mpa	1475	1850	NA
Kinematic viscosity @ 40^{o}C	cSt	2.25	4.5	1.9-6.0
Sulfur	%	0.25	0.0	0.05
Oxygen	%	0.3	10	11
Air fuel ratio (stochiometric)	--	14.86	14.2	13.8
Lower calorific value	kJ/kg	42 000	38000	37 518
Flash point (Open cup)	^{o}C	66	180	130
Molecular weight	--	226	280	292
Preheated temperature	^{o}C	--	60	--
Colour	--	Light yellow	Yellowish orange	---

The test fuels used in the experimentation were pure diesel and linseed oil based biodiesel. The schematic diagram of the experimental setup with test fuels is shown in Figure 1. The specifications of the experimental engine are shown in Table 2. The combustion chamber consisted of a direct injection type with no special arrangement for swirling motion of air. The engine was connected to an electric dynamometer for measuring its brake power. Burette method was used for finding fuel consumption of the engine. Air-consumption of the engine was measured by an air-box method (Air box was provided with an orifice meter and U-tube water manometer).

The naturally aspirated engine was provided with water-cooling system in which inlet temperature of water was maintained at 80°C by adjusting the water flow rate. Engine oil was provided with a pressure feed system. No temperature control was incorporated, for measuring the lube oil temperature. Copper shims of suitable size were provided (to vary the length of plunger of pump barrel) in between the pump body and the engine frame, to vary the injection timing and its effect on the performance of the engine was studied, along with the change of injector opening pressure from 190 bar to 270 bar (in steps of 40 bar) using nozzle testing device. The maximum injector opening pressure was restricted to 270 bar due to practical difficulties involved. Exhaust gas temperature was measured with thermocouples made of iron and iron-constantan.

Table 2: Specifications of the Test Engine

Description	Specification
Engine make and model	Kirloskar (India) AV1
Maximum power output at a speed of 1500 rpm	3.68 kW
Number of cylinders ×cylinder position× stroke	One × Vertical position × four-stroke
Bore × stroke	80 mm × 110 mm
Method of cooling	Water cooled
Rated speed (constant)	1500 rpm
Fuel injection system	In-line and direct injection
Compression ratio	16:1
BMEP @ 1500 rpm	5.31 bar
Manufacturer's recommended injection timing and pressure	27°bTDC × 190 bar
Dynamometer	Electrical dynamometer
Number of holes of injector and size	Three × 0.25 mm
Type of combustion chamber	Direct injection type
Fuel injection nozzle	Make: MICO-BOSCH No- 0431-202-120/HB
Fuel injection pump	Make: BOSCH: NO- 8085587/1

The specifications of the sound analyzer were given in Table 3.

Table 3: Specifications of Sound Analyzer

Name of the Analyzer	Measuring Range	Precision	Resolution
Sound Analyzer	0-150 Decibels	1 decibel	1 decibel

Different operating conditions of the biodiesel were normal temperature and preheated temperature. Different injector opening pressures attempted in this experimentation were 190 bar, 230 bar and 270 bar. Various injection timings attempted in the investigations were 27-34°bTDC. 1. Engine, 2. Electical Dynamometer, 3. Load Box, 4. Orifice

flow meter, 5.U-tube water manometer, 6.Air box, 7.Fuel tank, 8, Pre-heater, 9.Burette, 10. Exhaust gas temperature indicator, 11.Outlet jacket water temperature indicator, 12. Outlet-jacket water flow meter,

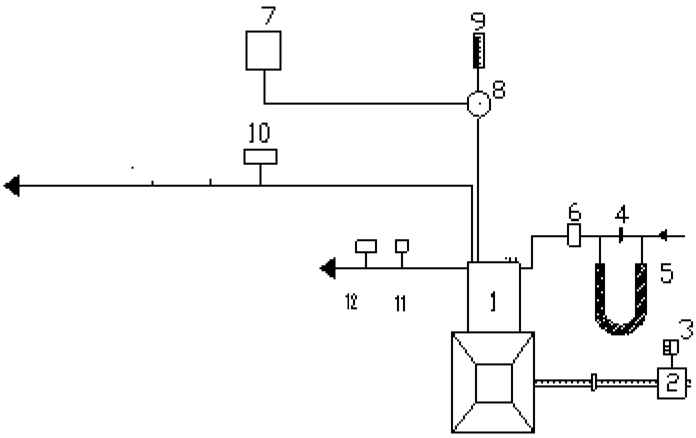

Figure 1: Schematic Diagram of Experimental Set-up

Few Definitions of IC Engine Parameters

Brake thermal efficiency (BTE); It is the ratio of brake power of the engine to the energy supplied to the engine. Brake power was measured with dynamometer. Energy supplied to the engine is the product of rate of fuel consumed (m_f)and calorific value (c_v)of the fuel. Higher the efficiency better the performance of the engine is.

$$\boldsymbol{BTE = \frac{BP}{m_{f \times CV}}}$$

Brake specific energy consumption (BSEC): It is measured at full load operation of the engine. Lesser the value, the better the performance of the engine. It is defined as energy consumed by the engine in producing 1 kW brake power. When different fuels having different properties are tested in engine, brake specific fuel consumption is not the criteria to evaluate the performance of the engine. Full BTE and BSEC at full load are important parameters to be considered to evaluate the performance of the engine.

$$BSEC = \frac{1}{BTE}$$

Coolant Load: Product of mass flow rate of coolant, specific heat of coolant, rise of temperature of the coolant between inlet conditions and outlet conditions.

Volumetric Efficiency: It is the ratio of the volume of air drawn into a cylinder to the piston displacement.

Recommended Injection Timing: It is the injection timing of the engine with maximum efficiency of the engine with minimum pollution levels.

Calculation of Actual Discharge of Air: By means of water tube manometer and an orifice flow meter, head of air (h_a) can be calculated. Velocity of air (V_a) can be calculated using the formula $V_a = \sqrt{2gh_a}$; Actual discharge of air $= c_d a \sqrt{2gh_a}$, where a= area of an orifice flow meter, c_d = Coefficient of discharge.

RESULTS AND DICUSSIONS

Results and discussion were made in two parts such as 1. Determining optimum injection timing with CE and engine with LHR combustion chamber, 2) Determine the performance parameters 3) Determine the Combustion

characteristics 4) determining the exhaust emissions. The performance of diesel fuel in conventional engine and LHR combustion chamber was taken from Reference [34]. The optimum injection timing with conventional engine was 31^{o}bTDC, while with LHR combustion chamber it was 30^{o}bTDC.

Determination of Optimum Injection Timing

The performance of diesel fuel in CE and LHR combustion chamber was taken from Reference [31]. The optimum injection timing with conventional engine with pure diesel operation was 31^{o}bTDC, while it was 30^{o}bTDC for LHR combustion chamber.

Comparative studies were made between CE and LHR combustion chamber with different operating conditions of the biodiesel with varied injection timing and injector opening pressure. The results were compared with standard diesel under the same conditions.

Performance Parameters

Curves from Figure 2 indicate that at recommended injection timing, engine with biodiesel showed the compatible performance for entire load range when compared with the pure diesel operation. This may be due to the difference of viscosity between the diesel and biodiesel and calorific value of the fuel. The reason might be due to (1) higher initial boiling point and different distillation characteristics, (2) higher density and viscosity leads to narrower spray cone angle and higher spray penetration tip, leading to inferior combustion compared to neat diesel [35].

However, higher density of biodiesel compensates the lower value of the heat of combustion of the biodiesel thus giving compatible performance with engine. Biodiesel contains oxygen molecule in its molecular composition. Theoretical air requirement of biodiesel was low [Table 1] and hence lower levels of oxygen were required for its combustion. Brake thermal efficiency increased with the advanced injection timing with conventional engine with the biodiesel at all loads. This was due to initiation of combustion at earlier period and efficient combustion with increase of air entrainment [31] in fuel spray giving higher brake thermal efficiency. Brake thermal efficiency increased at all loads when the injection timing was advanced to 31^{o}bTDC with the engine at the normal temperature of biodiesel. The increase of brake thermal efficiency at optimum injection timing over the recommended injection timing with biodiesel with conventional engine could be attributed to its longer ignition delay and combustion duration [31].

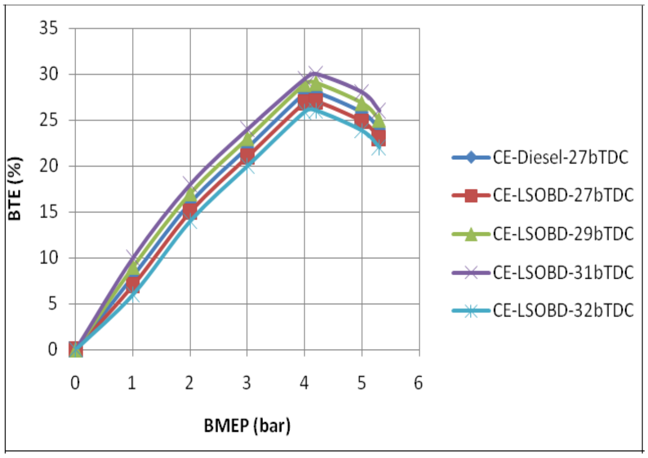

Figure 2: Variation of Brake Thermal Efficiency (BTE) with Brake Mean Effective Pressure (LDOBD) in Conventional Engine (CE) at Different Injection Timings with Biodiesel (LSOBD) Operation

Similar trends were noticed with preheated biodiesel. Preheating of the biodiesel reduced the viscosity, which improved the spray characteristics of the oil, causing efficient combustion thus improving brake thermal efficiency.

From Figure 3, it is observed that LHR version of the engine at recommended injection timing showed the improved performance at all loads compared with CE with pure diesel operation. High cylinder temperatures [31] helped in improved evaporation and faster combustion of the fuel injected into the combustion chamber. Reduction of ignition delay of the vegetable oil in the hot environment of the LHR combustion chamber improved heat release rates and efficient energy utilization. The optimum injection timing was found to be 30^{o}bTDC with LHR combustion chamber with different operating conditions of biodiesel operation. Since the hot combustion chamber of LHR combustion chamber reduced ignition delay and combustion duration and hence the optimum injection timing was obtained [31] earlier with LHR combustion chamber when compared to conventional engine with the biodiesel operation.

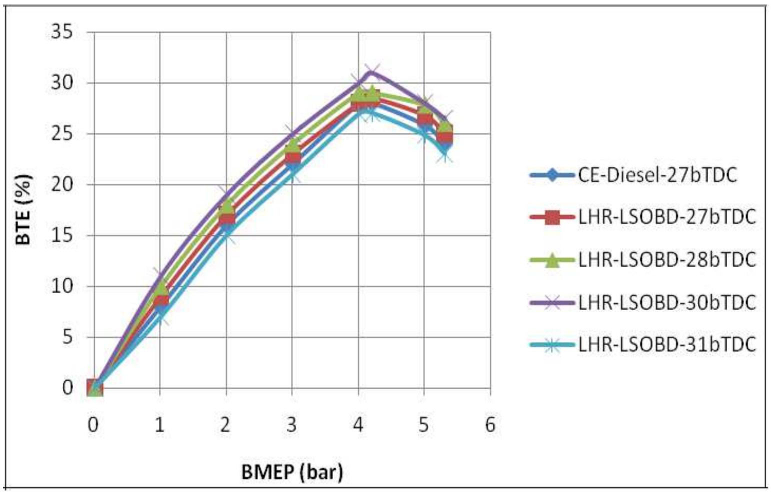

Figure 3: Variation of Brake Thermal Efficiency (BTE) with Brake Mean Effective Pressure (BMEP) in LHR Combustion Chamber at Different Injection Timings with Biodiesel (LSOBD) Operation

Part load variations were very small and minute for the performance parameters and exhaust emissions. The effect of varied injection timing on the performance was discussed with the help of bar charts while the effect of injector opening pressure and preheating of biodiesel was discussed with the help of Tables.

From Figure 4, it was noticed that peak brake thermal efficiency (BTE) with engine with LHR combustion chamber with pure diesel operation was lower in comparison with conventional engine at recommended (2%) and optimized injection timings (6%). Engine with LHR combustion chamber [31] with pure diesel operation deteriorated the performance in comparison with conventional engine. As the combustion chamber was insulated to greater extent, it was expected that high combustion temperatures would be prevalent in LHR combustion chamber. It tends to decrease the ignition delay thereby reducing pre-mixed combustion as a result of which, less time was available for proper mixing of air and fuel in the combustion chamber leading to incomplete combustion, with which peak BTE decreased. More over at this load, friction and increased diffusion combustion resulted from reduced ignition delay.

Peak BTE with LHR combustion chamber with biodiesel operation was higher in comparison with conventional engine at recommended and optimized injection timings.

This was due to higher degree of insulation provided in the piston, liner (with the provision of air gap with superni-90 inserts) and cylinder head reduced the heat rejection leading to improve the thermal efficiency. This was also

because of improved evaporation rate of the biodiesel. High cylinder temperatures [31] helped in improved evaporation and faster combustion of the fuel injected into the combustion chamber. Reduction of ignition delay of the vegetable oil in the hot environment of the engine with LHR combustion chamber improved heat release rates and efficient energy utilization.

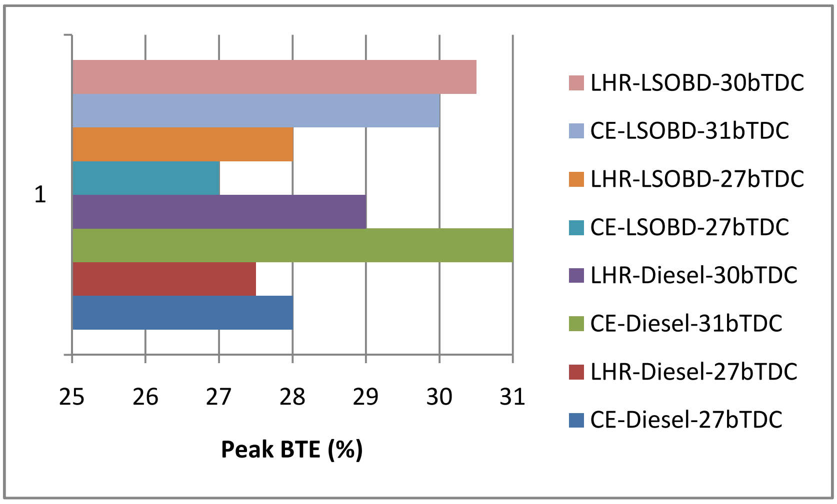

Figure 4: Bar Charts Showing the Variation of Peak Brake Thermal Efficiency (BTE) with Test Fuels at Recommended and Optimized Injection Timings at an Injector Opening Pressure of 190 Bar in Conventional Engine and Ceramic Coated LHR Combustion Chamber

Injector opening pressure was varied from 190 bar to 270 bar to improve the spray characteristics and atomization of the test fuels and injection timing is advanced from 27 to 34^{o}bTDC for CE and LHR combustion chamber. As it is observed from Table 4, peak brake thermal efficiency increased with increase in injector opening pressure at different operating conditions of the biodiesel.

For the same physical properties, as injector opening pressure increased droplet diameter decreased influencing the atomization quality, and more dispersion of fuel particle, resulting in turn in better vaporization, leads to improved air-fuel mixing rate, as extensively reported in the literature [16-18,35]. In addition, improved combustion leads to less fuel consumption.

Performance improved further with the preheated biodiesel when compared with normal biodiesel. This was due to reduction in viscosity of the fuel. Preheating of the biodiesel reduced the viscosity, which improved the spray characteristics of the oil causing efficient combustion thus improving brake thermal efficiency. The cumulative heat release was more for preheated biodiesel [35] than that of biodiesel and this indicated that there was a significant increase of combustion in diffusion mode [35]. This increase in heat release [35] was mainly due to better mixing and evaporation of preheated biodiesel, which leads to complete burning.

Table 4: Data of Peak Brake Thermal Efficiency (BTE) and Brake Specific Energy Consumption at Full Load Operation

Injection Timing (^{o}bTDC)	Test Fuel	Peak BTE (%)						Brake Specific Energy Consumption at Peak Load Operation (kW/kW)					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27(CE)	DF	28	--	29	---	30	--	4.0	--	3.96	--	3.92	--
	LSOBD	27	27.5	27.5	28	28.5	29	4.02	3.96	3.96	3.94	3.94	3.96
27(LHR)	DF	27.5	--	28	--	29	--	4.3	--	4.2	--	4.1	--
	LSOBD	28	28.5	28.5	29	29	29.5	3.84	3.80	3.80	3.76	3.76	3.72
30(LHR)	DF	29		29.5		30		3.80		3.76		3.72	
	LSOBD	30.5	31	31	31.5	32	32.5	3.72	3.68	3.68	3.64	3.64	3.60
31(CE)	DF	31		31.5		32		3.6	--	3.7	--	3.8	---
	LSOBD	30	30.5	30.5	31	31	31.5	3.82	3.78	3.86	3.82	3.90	3.86

DF- Diesel fuel, LSOBD Biodiesel, NT- Normal temperature, PT- Preheated temperature

Generally brake specific fuel consumption, is not used to compare the two different fuels, because their calorific value, density, chemical and physical parameters are different. Performance parameter, BSEC, is used to compare two different fuels by normalizing brake specific energy consumption, in terms of the amount of energy released with the given amount of fuel.

From Figure 5, it was evident that brake specific energy consumption with LHR combustion chamber with pure diesel operation was higher in comparison with conventional engine at recommended (8%)and optimized injection timings (6%). This was due to reduction of ignition delay with pure diesel operation with LRH engine as hot combustion chamber was maintained by engine with LHR combustion chamber. With biodiesel operation, BSEC was lower with LHR combustion chamber at recommended injection timing (5%) and at optimized injection timing (3%) in comparison with conventional engine.

BSEC was higher with conventional engine due to due to higher viscosity, poor volatility and reduction in heating value of biodiesel lead to their poor atomization and combustion characteristics. The viscosity effect, in turn atomization was more predominant than the oxygen availability [35] in the blend leads to lower volatile characteristics and affects combustion process**.** BSEC was improved with LHR combustion chamber with lower substitution of energy in terms of mass flow rate.

BSEC decreased with advanced injection timing with test fuels. This was due to initiation of combustion and substitution of lower energy as seen From the Figure 6.

BSEC of biodiesel is almost the same as that of neat diesel fuel as shown in Figure 6. Even though viscosity of biodiesel is slightly higher than that of neat diesel, inherent oxygen of the fuel molecules improves the combustion characteristics. This is an indication of relatively more complete combustion [35].

From the Table 4 it is noticed that BSEC at full load operation decreased with increase of injector opening pressure with different operating conditions of the test fuels. This was due to increase of air entrainment [35] in fuel spray giving lower BSEC.

BSEC decreased with the preheated biodiesel at full load operation when compared with normal biodiesel. Preheating of the biodiesel reduced the viscosity, which improved the spray characteristics of the oil.

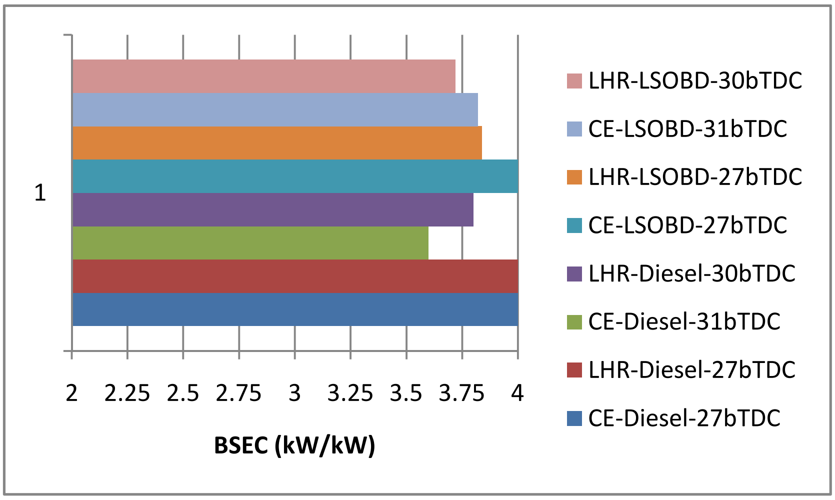

Figure 5: Bar Charts Showing the Variation of Brake Specific Energy Consumption (BSEC) at Peak Load Operation with Test Fuels at Recommended and Optimized Injection Timings at an Injector Opening Pressure of 190 Bar in CE and LHR Combustion Chamber

From Figure 6, it was observed that exhaust gas temperature (EGT) with engine with LHR combustion chamber with pure diesel operation was higher in comparison with conventional engine at recommended (6%) and optimized injection timings (12%).

This was due to reduction of ignition delay with pure diesel operation with LRH engine as hot combustion chamber was maintained by engine with LHR combustion chamber. This indicated that heat rejection was restricted through the piston, liner and cylinder head, thus maintaining the hot combustion chamber as result of which the exhaust gas temperature increased.

EGT with engine with LHR combustion chamber with biodiesel operation was marginally higher in comparison with conventional engine at recommended (6%) and optimized injection timings (3%). This was due to reduction of ignition delay in the hot environment with the provision of the insulation in the LHR combustion chamber, which caused the gases expand in the cylinder giving higher work output and lower heat rejection.

EGT decreased with advanced injection timing with test fuels as seen from the Figure. This was because, when the injection timing was advanced, the work transfer from the piston to the gases in the cylinder at the end of the compression stroke was too large, leading to reduce in the value of EGT.

Though the calorific value (or heat of combustion) of fossil diesel is more than that of biodiesel; the density of the biodiesel was higher therefore greater amount of heat was released in the combustion chamber leading to higher exhaust gas temperature with conventional engine, which confirmed that performance was compatible with conventional engine with biodiesel operation in comparison with pure diesel operation. Similar findings were obtained by other studies [21].

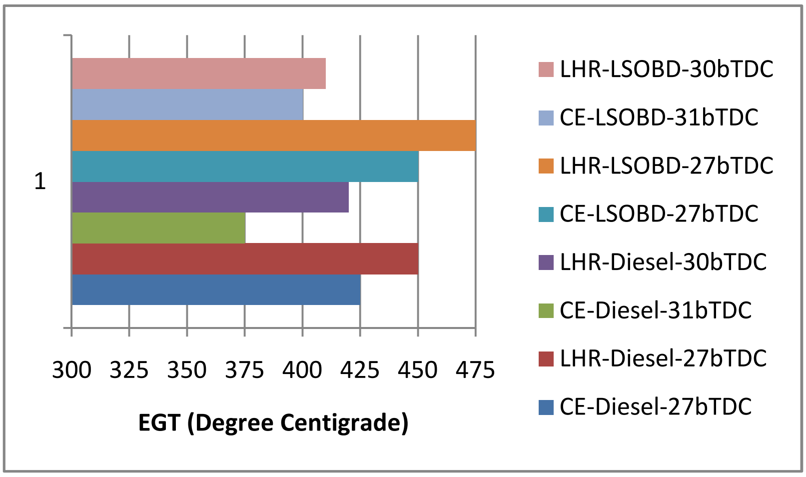

Figure 6: Bar charts Showing the Variation of Exhaust Gas Temperature (EGT) at Peak Load Operation with Test Fuels at Recommended and Optimized Injection Timings at an Injector Opening Pressure of 190 Bar in Conventional Engine and LHR Combustion Chamber

From the Table 5, it is noticed that the exhaust gas temperatures of preheated biodiesel were higher than that of normal biodiesel, which indicates the increase of diffused combustion [35] due to high rate of evaporation and improved mixing between methyl ester and air. Therefore, as the fuel temperature increased, the ignition delay decreased and the main combustion phase (that is, diffusion controlled combustion) increased [35], which in turn raised the temperature of exhaust gases. The value of exhaust gas temperature decreased with increase in injector opening pressure with test fuels as it is evident from the Table 5. This was due to improved spray characteristics of the fuel with increase of injector opening pressure.

Exhaust gas temperature was lower with diesel operation with conventional engine when compared with biodiesel operation, while EGT was lower with LHR combustion chamber with biodiesel operation in comparison with diesel operation. Hence conventional engine was more suitable for diesel operation, while LHR combustion chamber was suitable for biodiesel operation.

Table 5: Data of Exhaust Gas Temperature (EGT) and Coolant Load at Full Load Operation

Injection Timing (°bTDC)	Test Fuel	EGT at Peak Load Operation (Degree Centigrade)						Coolant Load at Peak Load Operation (kW)					
		Injector Opening Pressure (Bar)						Injector Opening Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27(CE)	DF	425	--	410	---	395	--	4.0	---	4.2	--	4.4	---
	LSOBD	450	490	410	450	370	410	4.2	4.0	4.4	4.2	4.6	4.4
27(LHR)	DF	450	--	430	--	410	--	3.8	--	3.6	--	3.4	--
	LSOBD	475	500	450	475	425	450	3.6	3.4	3.4	3.2	3.2	3.0
30(LHR)	DF	420	--	400	--	380	--	3.6		3.8		4.0	
	LDOBD	410	430	440	470	460	480	3.4	3.2	3.2	3.0	3.0	2.8
31(CE)	DF	375	---	350	---	325	--	4.2	--	4.4	--	4.6	---
	LSOBD	400	440	420	460	440	420	4.4	4.2	4.6	4.4	4.8	4.6

DF- Diesel fuel, LSOBD Biodiesel, NT- Normal temperature, PT- Preheated temperature

Figure 7 indicates that coolant load with LHR combustion chamber with pure diesel operation was lower (5% and 14%) at recommended and optimized injection timings respectively in comparison with conventional engine. This was due insulation provided with LHR combustion chamber.

Coolant load with engine with LHR combustion chamber with biodiesel operation was lower at recommended (14% and optimized injection timings (23%) respectively in comparison with conventional engine. This was due insulation provided with LHR combustion chamber.

In case of conventional engine, un-burnt fuel concentration reduced with effective utilization of energy, released from the combustion, coolant load with test fuels increased marginally at peak load operation, due to un-burnt fuel concentration reduced with effective utilization of energy, released from the combustion, with increase of gas temperatures, when the injection timing was advanced to the optimum value. However, the improvement in the performance of the conventional engine was due to heat addition at higher temperatures and rejection at lower temperatures, while the improvement in the efficiency of the LHR combustion chamber was due to recovery from coolant load at their respective optimum injection timings with test fuels. Murali Krishna [31] noticed the similar trend at optimum injection timing with his LHR combustion chamber.

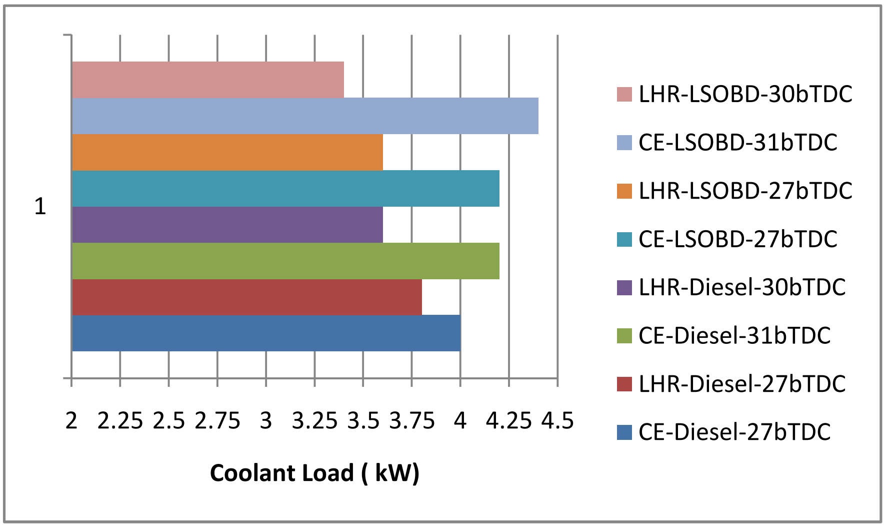

Figure 7: Bar Charts Showing the Variation of Coolant Load at Peak Load Operation with Test Fuels at Recommended and Optimized Injection Timings at an Injector Opening Pressure of 190 Bar in Conventional Engine and LHR Combustion Chamber

From Table 5, it is seen that coolant load increased marginally in the conventional engine while it decreased in the LHR combustion chamber with increase of the injector opening pressure with test fuels. This was due to the fact with increase of injector opening pressure with conventional engine, increased nominal fuel spray velocity resulting in improved fuel-air mixing with which gas temperatures increased. The reduction of coolant load in the LHR combustion chamber was not only due to the provision of the insulation but also it was due to better fuel spray characteristics and increase of air-fuel ratios causing decrease of gas temperatures and hence the coolant load.

Coolant load decreased marginally with preheating of biodiesel. This was due to improved air fuel ratios [31] with improved spray characteristics.

Figure 9 denotes that sound levels were higher (18% and 16%) with engine with LHR combustion chamber with pure diesel operation at recommended and optimized injection timings respectively in comparison with conventional engine. This showed that performance deteriorated with LHR combustion chamber with pure diesel operation. This was due to reduction of ignition delay.

Sound levels were lower with LHR combustion chamber with biodiesel operation at recommended (6%) and optimized injection timings (13%) respectively in comparison with conventional engine. This showed that performance improved with LHR combustion chamber with biodiesel operation.

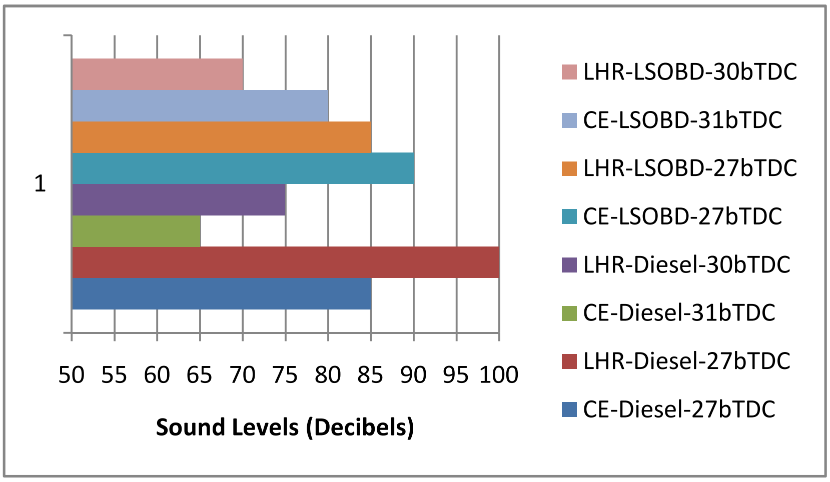

Figure 8: Bar Charts Showing the Variation of Sound Levels at Peak Load Operation with Test Fuels at Recommended and Optimized Injection Timings at an Injector Opening Pressure of 190 Bar

With advanced injection timings, air fuel ratios improved with early initiation of combustion hence sound levels got reduced with both versions of the engine with test fuels.

Table 6 denotes that the Sound levels decreased with increase of injector opening pressure with the test fuels. This was due to improved spray characteristic of the fuel, with which there was no impingement of the fuel on the walls of the combustion chamber leading to produce efficient combustion.

Sound intensities were lower at preheated condition of preheated biodiesel when compared with their normal condition. This was due to improved spray characteristics, decrease of density and viscosity of the fuel.

Table 6: Data of Sound Levels and Volumetric Efficiency with Test Fuels at Full Load Operation

Injection Timing (^{o}bTDC)	Test Fuel	Sound Levels at Peak Load Operation (Decibels)						Volumetric Efficiency (%) at Peak Load Operation					
		Injector Opening Pressure (Bar)						Injector Opening Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27(CE)	DF	85	--	80	--	95	--	85	--	86	--	87	--
	LSOBD	90	85	85	80	80	70	83	82	84	83	85	84
27(LHR)	DF	100	--	95	--	90	--	80		81		82	
	LSOBD	85	80	80	75	75	70	81	82	82	83	83	84
30 (LHR)	DF	75		70		65		81		82		83	
	LSOBD	70	65	65	60	60	55	82	82	83	84	84	85
31(CE)	DF	65	--	60	--	55	--	89	--	90	--	91	--
	LSOBD	80	75	85	80	90	85	87	88	87	89	88	87

DF- Diesel fuel, LSOBD Biodiesel, NT- Normal temperature, PT- Preheated temperature

Volumetric efficiency depends on density of the charge which intern depends on temperature of combustion chamber wall.

Figure 8 denotes that volumetric efficiencies were lower (6% and 9%) with LHR combustion chamber with pure diesel operation at recommended and optimized injection timings respectively in comparison with conventional engine.

Volumetric efficiency in the LHR combustion chamber decreased at full load operation when compared to the conventional engine at recommended and optimized injection timing with test fuels. This was due increase of temperature of incoming charge in the hot environment created with the provision of insulation, causing reduction in the density and hence the quantity of air. However, this variation in volumetric efficiency is very small between these two versions of the engine, as volumetric efficiency mainly depends [20] on speed of the engine, valve area, valve lift, timing of the opening or closing of valves and residual gas fraction rather than on load variation. Murali Krishna [35] also observed the similar trends in the value of volumetric efficiency.

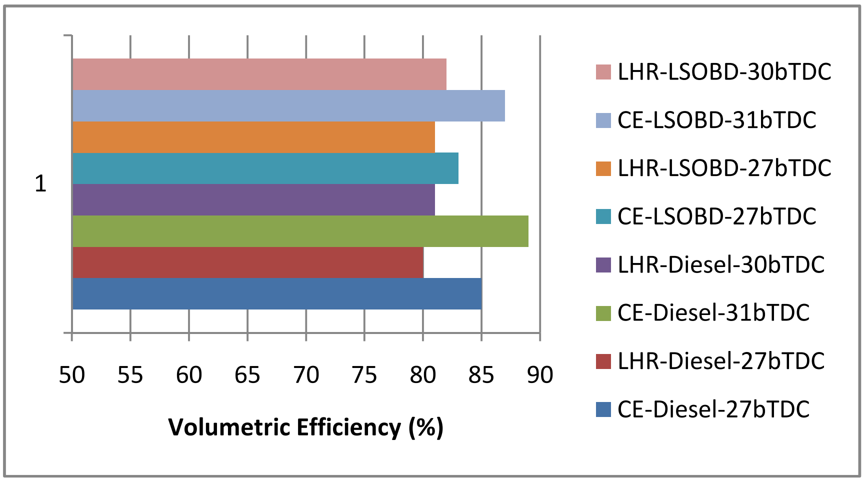

Figure 9: Bar Charts Showing the Variation of Volumetric Efficiency at Peak Load Operation with Test Fuels at Recommended and Optimized Injection Timings at an Injector Opening Pressure of 190 Bar in Conventional Engine and LHR Combustion Chamber

With biodiesel operation, volumetric efficiencies were lower with LHR combustion chamber at recommended (3%) and optimized injection timings (6%) respectively in comparison with conventional engine.

Volumetric efficiency was higher with pure diesel operation at recommended and optimized injection timing with conventional engine in comparison with biodiesel operation. This was due to increase of combustion chamber wall temperatures with biodiesel operation due to accumulation of un-burnt fuel concentration. This was also because of increase of combustion chamber wall temperature as exhaust gas temperatures increased with biodiesel operation in comparison with pure diesel operation.

Volumetric efficiency increased marginally with both versions of the engine with test fuels with advanced injection timing. This was due to decrease of combustion chamber wall temperatures with improved air fuel ratios [34].

From Table 6, it is evident that volumetric efficiency increased with increase of injector opening pressure with test fuels. This was due to improved fuel spray characteristics and evaporation at higher injection pressures leading to marginal increase of volumetric efficiency. This was also because of decrease of exhaust gas temperatures and hence combustion chamber wall temperatures. This was also due to the reduction of residual fraction of the fuel, with the increase of injector opening pressure.

Preheating of the biodiesel marginally decreased volumetric efficiency, when compared with the normal temperature of biodiesel, because of reduction of bulk modulus, density of the fuel and increase of exhaust gas temperatures.

Combustion Characteristics

Figure 10 indicates that LHR engine gave lower peak pressures (4%) at recommended injection timing and higher peak pressures (7%) with pure diesel operation in comparison with conventional engine.

From the Table 7, it is noticed that peak pressures at an injection timing of 27^{o} bTDC were lower in the LHR engine in comparison with the conventional engine with pure diesel operation. This was because the LHR engine exhibited higher temperatures of combustion chamber walls leading to continuation of combustion, giving peak pressures away from TDC. However, this phenomenon was nullified with advanced injection timing of 30^{o}bTDC on the same LHR engine with diesel operation because of reduced temperature of combustion chamber walls thus bringing the peak pressures closure to TDC. Similar findings were obtained by Reference [34].

Peak pressures increased by 4% and 2% with LHR engine with biodiesel operation at recommended and optimized injection timings respectively in comparison with conventional engine.

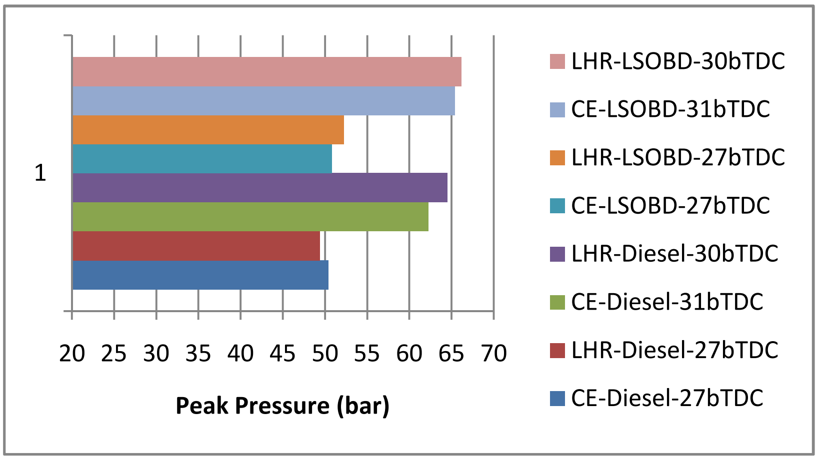

Figure 10: Bar Charts Showing the Variation of Peak Pressure at Peak Load Operation with Test Fuels at Recommended and Optimized Injection Timings at an Injector Opening Pressure of 190 Bar at full load operation

Peak pressure with LHR engine increased the mass-burning rate of the fuel in the hot environment leading to produce higher peak pressures. The advantage of using LHR engine for biodiesel was obvious as it could burn high viscous fuels.

From the Table 5, it is noticed that peak pressure for normal biodiesel was slightly higher than that of diesel fuel; even though biodiesel was having lower value of lower calorific value. Biodiesel advanced the peak pressure position as compared to fossil diesel because of its higher bulk modulus and cetane number. This shift is mainly due to advancement of injection due to higher density and earlier combustion due to shorter ignition delay caused by higher cetane number of biodiesel. When, a high density (or high bulk modulus) fuel is injected, the pressure wave travels faster from pump end to nozzle end, through a high pressure in-line tube [35]. This causes early lift of needle in the nozzle, causing advanced injection. Hence, the combustion takes place very close to TDC (lower value of time of occurrence of peak pressure) and the peak pressure slightly high due to existence of smaller cylinder volume near TDC.

Peak pressures increased with the increase of injector opening pressure and with the advancing of the injection timing with the test fuels. Peak pressure increased as injector opening increased. This may be due to smaller sauter mean

diameter [35] shorter breakup length, better dispersion, and better spray and atomization characteristics. This improves combustion rate in the premixed combustion phase.

However, the peak pressure of preheated biodiesel was less than that of normal biodiesel. When the engine is running on preheated biodiesel the fuel injection was slightly delayed, due to decrease in bulk modulus of biodiesel with the increase in fuel temperature. The reasons for lower peak pressures of preheated biodiesel was also attributed to earlier combustion caused by short ignition delay (due to faster evaporation of the fuel) at their preheated temperatures.

Figure 11 denotes that maximum rate of pressure rise (MRPR) was highest for normal diesel followed by the biodiesel. With biodiesel, as injector opening pressure increased, spray characteristic improved and in turn burned fuel increased again and in turn combustion rate increased in the premixed combustion phase [33]. Preheated biodiesel gave lower MRPR when compared with normal biodiesel as in the case of peak pressure. The trends of MRPR were similar to those of peak pressure in both versions of the combustion chamber with test fuels. With pure diesel operation, with engine with LHR combustion chamber, MRPR decreased by 22% at recommended injection timing and increased by 10% at optimized injection timing in comparison with CE. This was due to deteriorated combustion at recommended injection because of reduction of ignition delay and improved combustion at advanced injection timing with improved air fuel ratios.

With biodiesel operation, with engine with LHR combustion chamber, MRPR increased by 12% and 14% at recommended injection timing and optimized injection timing respectively in comparison with CE. This was because of improved combustion with biodiesel operation on engine with LHR combustion chamber as biodiesel required higher duration of combustion and hence engine with LHR combustion chamber was more suitable for it.

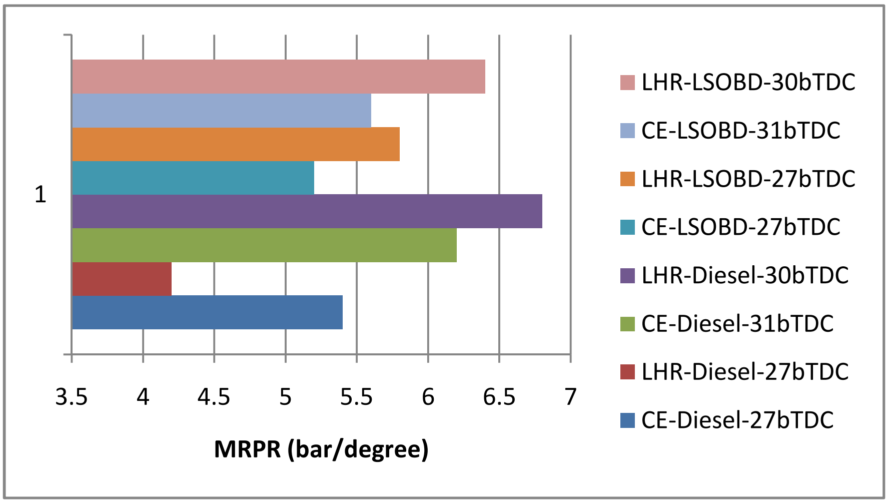

Figure 11: Bar Charts Showing the Variation of Maximum Rate of Pressure Rise (MRPR) at Peak Load Operation with Test Fuels at Recommended and Optimized Injection Timings at an Injector Opening Pressure of 190 Bar at Full Load Operation

The value of time of occurrence of peak pressure (TOPP) decreased (towards TDC) with the advancing of the injection timing and with increase of injector opening pressure at different operating conditions of the test fuels. This once again established the fact by observing marginal increase of peak pressure and higher TOPP, that biodiesel operation with conventional engine showed compatible performance when compared with LHR engine. Preheating of the biodiesel showed lower TOPP, compared with biodiesel at normal temperature. This once again confirmed by observing the lower TOPP, the performance of the engine improved with the preheated biodiesel compared with the normal biodiesel.

Table 7: Data of Combustion Characteristics at Full Load Operation

Injection Timing (^{o}bTDC)	Test Fuel	PP (Bar) Injector Opening Pressure				MRPR (Bar/Deg) Injector opening Pressure				TOPP (Deg) Injector Opening Pressure			
		190		270		190		270		190		270	
		NT	PT	NT	PT								
27(CE)	DF	50.4	--	53.5	---	5.4	--	6.0	--	10		9	
	LSOBD	50.8	49.8	51.6	50.8	5.2	3.9	5.2	4.2	11	10	10	9
27(LHR)	DF	49.4	--	50.2	--	4.2		3.8		11	10	10	9
	LSOBD	52.2	51.1	51.1	50.3	5.8	5.6	5.2	4.8	10	9	10	9
30(LHR)	LSOBD	66.1	65.4	65.4	64.1	6.4	6.0	6.2	5.6	8	8	8	8
	DF	64.5	-	62.6	--	6.8		6.4		8		8	
31(CE)	DF	62.2	--	61.9	--	6.2	--	6.8.	--	8		8	
	LSOBD	65.4	64.1	63.4	62.2	5.6	4.4	6.0	4.8	8	8	8	8

This trend of increase of maximum rate of pressure rise indicated improved and faster energy substitution and utilization by biodiesel in engine, which could replace 100% diesel fuel. That too, all these combustion characters were within the limits hence biodiesel can be effectively substituted for diesel fuel.

Exhaust Emissions

This section deals with i) effect of smoke and NOx emissions on human health and its impact on environment, ii) Comparative study of smoke and NOx emissions in CE and engine with LHR combustion chamber with varied injector opening pressure and injection timing with different operating conditions of the vegetable oil.

Smoke and NOx are the emissions from diesel engine cause [34] health hazards like inhaling of these pollutants cause severe headache, tuberculosis, lung cancer, nausea, respiratory problems, skin cancer, hemorrhage, etc. The contaminated air containing carbon dioxide released from automobiles reaches ocean in the form of acid rain, there by polluting water. Hence control of these emissions is an immediate task and important. Figure 12 denotes that smoke levels increased by 25% and 13% with engine with LHR combustion chamber with pure diesel operation at recommended and optimized injection timings respectively in comparison with conventional engine.

This was due to fuel cracking at higher temperature, leading to increase in smoke density. Higher temperature of engine with LHR combustion chamber produced increased rates of both soot formation and burn up. The reduction in volumetric efficiency [34] and air-fuel ratio [34] was responsible factors for increasing smoke levels in the LHR engine near the peak load operation of the engine. As expected, smoke increased in the LHR engine because of higher temperatures and improper utilization of the fuel consequent upon predominant diffusion combustion [35].

When injection timing was advanced to their respective optimum values with both versions of the engine, smoke levels decreased with diesel operation. This was due to increase of air fuel ratios, causing effective combustion in both versions of the engine. The reason for reduction of smoke levels in the LHR engine was reduction of gas temperatures, with the availability of more of oxygen when the injection timing was advanced to its optimum value. This was confirmed by the observation of improved air fuel ratios [34] with the increase of injector opening pressure and with the advancing of the injection timing with both versions of the combustion chamber. However at optimum injection timings, smoke levels were lower in the conventional engine compared to the engine with LHR combustion chamber, due to improved air fuel ratios [34] and volumetric efficiency in the conventional engine.

Smoke levels decreased by 28% and 22% with engine with LHR combustion chamber with biodiesel operation at recommended and optimized injection timings respectively in comparison with conventional engine. Engine with LHR combustion chamber marginally reduced smoke levels due to efficient combustion and less amount of fuel accumulation on the hot combustion chamber walls of the LHR combustion chamber at different operating conditions of the biodiesel compared to the conventional engine

Conventional engine with pure diesel operation gave lower smoke levels in comparison with biodiesel.

This was due to the higher value of ratio of C/H [$C_{57}H_{98}O_6$], (C= Number of carbon atoms and H= Number of hydrogen atoms in fuel composition (higher the value of this ratio means, number of carbon atoms are higher leading to produce more carbon dioxide and more carbon monoxide and hence higher smoke levels) of fuel composition. The increase of smoke levels was also due to decrease of air-fuel ratios [35] and volumetric efficiency [35] with biodiesel compared with pure diesel operation. Smoke levels were related to the density of the fuel. Since biodiesel has higher density compared to diesel fuel, smoke levels were higher with biodiesel. Smoke levels decreased [35] at the respective optimum injection timing with test fuels. This was due to initiation of combustion at early period. This was due to increase of air entrainment, at the advanced injection timings, causing lower smoke levels. Smoke levels were found to be lower with biodiesel operation compared with diesel operation with engine with LHR combustion chamber. The inherent oxygen of biodiesel might have provided some useful interactions between air and fuel, particularly in the fuel-rich region. Certainly, it is evident proof of the oxygen content of biodiesels enhanced the oxidation of hydrocarbon reactions thus reducing smoke levels. The data from Table 4 shows a decrease in smoke levels with increase of injector opening pressure, with different operating conditions of the biodiesel.

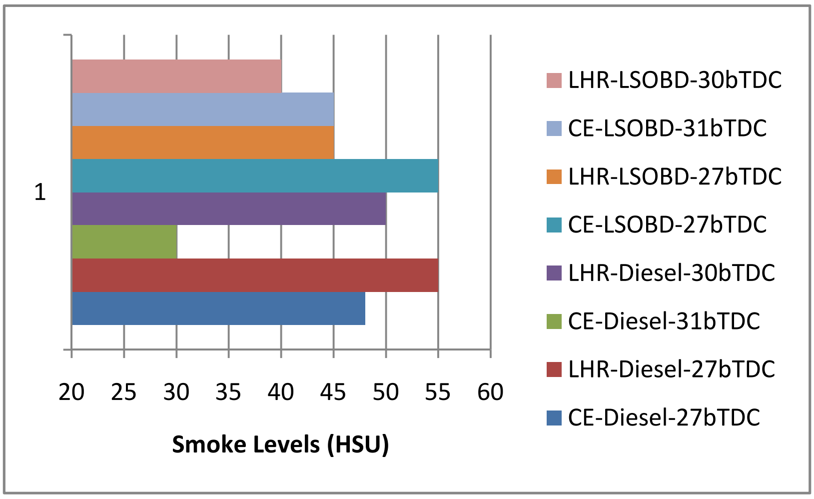

Figure 12: Bar Charts Showing the Variation of Smoke Levels in Hartridge Smoke Unit (HSU) at Peak Load Operation with Test Fuels at Recommended and Optimized Injection Timings at an Injector Opening Pressure of 190 Bar at Full Load Operation

This was due to improvement in the fuel spray characteristics at higher injector opening pressure causing lower smoke levels. Even though viscosity of biodiesel was higher than diesel, high injector opening pressure improves spray characteristics, hence leading to a shorter physical delay period. The improved spray also leads to better mixing of fuel and air resulting in turn in fast combustion. This will enhance the performance [35]

Preheating of the biodiesel reduced smoke levels, when compared with normal temperature of the biodiesel. This was due to i) the reduction of density of the biodiesel, as density was directly related to smoke levels, ii) the reduction

of the diffusion combustion proportion with the preheated biodiesel, iii) the reduction of the viscosity of the biodiesel with which the fuel spray does not impinge on the combustion chamber walls of lower temperatures rather than it directed into the combustion chamber**.**

NOx are the precursor pollutants which can combine to form photochemical smog. These irritate the eyes and throat, reduces the ability of blood to carry oxygen to the brain and can cause headaches, and pass deep into the lungs causing respiratory problems for the human beings. Long-term exposure has been linked with leukemia. Therefore, the major challenge for the existing and future diesel engines is meeting the very tough emission targets at affordable cost, while improving fuel economy.

Temperature and availability of oxygen are two favorable conditions to form NOx levels. At peak load, NOx levels increased with test fuels at recommended injection timing due to higher peak pressures, temperatures as larger regions of gas burned at close-to-stoichiometric ratios.

Figure 13 denotes that NOx levels increased by 41% and 5% with engine with LHR combustion chamber with pure diesel operation at recommended and optimized injection timings respectively in comparison with conventional engine. At peak load operation, due to the reduction of air fuel ratio with engine with LHR combustion chamber, which was approaching to the stoichiometric ratio, causing more NOx concentrations as combustion chamber was maintained more hot due to the insulating parts.

NOx levels increased by 29% and 9% with engine with LHR combustion chamber with biodiesel operation at recommended and optimized injection timings respectively in comparison with conventional engine. Increase of combustion temperatures [35] with the faster combustion and improved heat release rates [35] in the LHR engine cause higher NOx levels in comparison with conventional engine with biodiesel operation.

From the Table 8, it was observed that increasing the injection advance resulted in higher combustion temperatures and increase of resident time leading to produce more NOx concentration in the exhaust of conventional engine with test fuels.

At the optimum injection timing, the LHR engine with test fuels produced lower NOx emissions, at peak load operation compared to the same version of the engine at the recommended injection timing. This was due to decrease of combustion temperatures [36] with improved air fuel ratios.

Table 8: Data of Exhaust Emissions at Peak Load Operation

Injection Timing (^{o}bTDC)	Test Fuel	Smoke Levels (Hartridge Smoke Unit)						NOx Levels (ppm)					
		Injector Opening Pressure (Bar)						Injector Opening Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27(CE)	DF	48	--	38	--	34	--	850	----	900	----	950	---
	LSOBD	55	50	50	45	45	40	950	875	1000	925	1050	975
27LHR)	DF	55	--	50	--	45	--	1100	--	1050	--	1000	--
	LSOBD	45	40	40	35	35	30	1225	1175	1175	1125	1125	1075
30(LHR)	LSOBD	40	35	35	30	30	25	1175	1125	1125	1075	1075	1025
	DF	50	--	45	--	40	--	1050	--	1000	--	950	--
31(CE)	DF	30	--	30	--	35	--	1100	--	1150	--	1200	--
	LSOBD	45	40	40	35	35	30	1150	1100	1200	1150	1250	1200

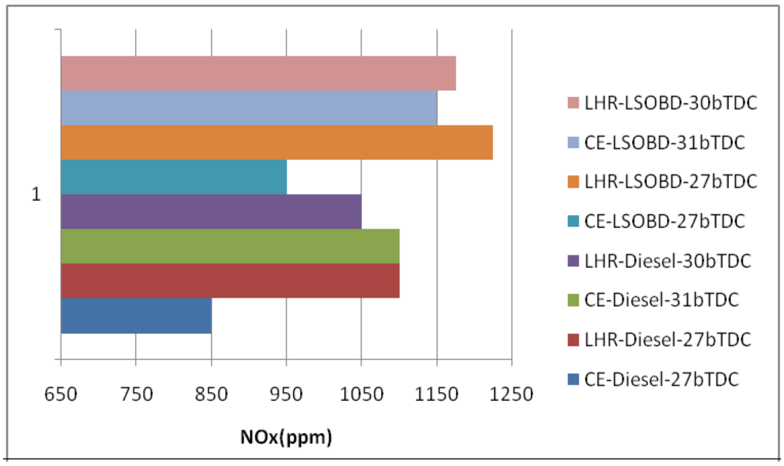

Figure 13: Bar Charts Showing the Variation of Nox Levels at Peak Load Operation with Test Fuels at Recommended and Optimized Injection Timings at an Injector Opening Pressure of 190 Bar at Full Load Operation

Biodiesel with both versions of the engine gave higher NOx levels than pure diesel operation. The linseed oil based biodiesel having long carbon chain (C_{20}-C_{32}) [31] recorded more NOx than that of fossil diesel having both medium (C_8-C_{14}) as well as long chain (C_{16}-C_{28}). The increase in NOx emission might be an inherent characteristic of biodiesel due to the presence of 54.9% of mono-unsaturated fatty acids (MUFA) and 18% of poly-unsaturated fatty acids (PUFA). That means, the long chain unsaturated fatty acids (MUFA and FUPA) such as oleic C18:1 and linoliec C18:2 fatty acids are mainly responsible for higher levels of NOx emission [33]. Another reason for higher NOx levels is the oxygen (10%) present in the methyl ester. The presence of oxygen in normal biodiesel leads to improvement in oxidation of the nitrogen available during combustion. This will raise the combustion bulk temperature responsible for thermal NOx formation Many researchers reported that oxygen [33] and nitrogen [35] content of biodiesel can cause an increase in NO*x* emissions. The production of higher NOx with biodiesel fueling is also attributable to an inadvertent advance of fuel injection timing due to higher bulk modulus of compressibility, with the in-line fuel injection system.

From the Table 8, it is noted that these levels increased with increase of injector opening pressure with different operating conditions of biodiesel. NO*x* slightly increased with test fuels as injector opening pressure increased. As seen from the Table 4, that peak brake thermal efficiency increased as injector opening pressure increased. The increase in peak brake thermal efficiency was proportional to increase in injector opening pressure. Normally, improved combustion causes higher peak brake thermal efficiency due to higher combustion chamber pressure [35] and temperature and leads to higher NO*x* formation. This is an evident proof of enhanced spray characteristics, thus improving fuel air mixture preparation and evaporation process.

NOx levels decreased with preheating of the biodiesel as noticed from the Table 8. The fuel spray properties may be altered due to differences in viscosity and surface tension. The spray properties affected may include droplet size, droplet momentum, degree of mixing, penetration, and evaporation. The change in any of these properties may lead to different relative duration of premixed and diffusive combustion regimes. Since the two burning processes (premixed and diffused) have different emission formation characteristics, the change in spray properties due to preheating of the vegetable oil (s) are lead to reduction in NOx formation. As fuel temperature increased, there was an improvement in the ignition quality, which will cause shortening of ignition delay. A short ignition delay period lowers the peak combustion temperature which suppresses NOx formation [33, 35]. Lower levels of NOx is also attributed to retarded injection,

improved evaporation, and well mixing of preheated biodiesel due to their viscosity at preheated temperatures. Biodiesel has higher value of NOx emissions followed by diesel. This was because of inherent nature of biodiesel as it has oxygen molecule in its composition.

CONCLUSIONS

- Peak BTE with LHR combustion chamber with biodiesel operation was higher in comparison with conventional engine at recommended (4%) and optimized injection timings (2%).
- BSEC was lower with LHR combustion chamber with biodiesel operation in comparison with conventional engine at recommended injection timing (5%) and optimum injection timing (3%).
- EGT with LHR combustion chamber with biodiesel operation was marginally higher in comparison with conventional engine at recommended (6%) and optimized injection timings (3%).
- Coolant load with LHR combustion chamber with biodiesel operation was lower (14% and 23%) at recommended and optimized injection timings respectively in comparison with conventional engine. This was due insulation provided with LHR combustion chamber.
- Sound levels were lower (6% and 13%) with LHR combustion chamber with biodiesel operation at recommended and optimized injection timings respectively in comparison with conventional engine.
- Volumetric efficiencies were lower (3% and 6%) with LHR combustion chamber with biodiesel operation at recommended and optimized injection timings respectively in comparison with conventional engine.
- With increase of injection pressure with both versions of the engine with test fuels.
- Peak brake thermal efficiency increased. At peak load operation- brake specific energy consumption decreased, exhaust gas temperature decreased, volumetric efficiency increased, coolant load increased (CE), and sound levels decreased.
- Peak brake thermal efficiency increased, at peak load operation- brake specific energy consumption decreased, exhaust gas temperature increased(CE), volumetric efficiency decreased(CE), coolant load decreased, sound levels decreased.
- When compared with conventional engine, with biodiesel operation, at recommended and optimized injection timings, at full load operation, engine with LHR combustion chamber decreased smoke levels by 28% and 22%, increased NOx levels by 29% and 9%, increased peak pressure by 4% and 2% and increased maximum rate of pressure rise by 12% and 14% at full load operation.
- With increase of injection pressure with both versions of the combustion chamber with test fuels, smoke levels and NOx levels decreased.
- With preheating of biodiesel with both versions of the combustion chamber, smoke levels and NOx levels decreased.

All the combustion parameters were within the limits and hence biodiesel can be substituted for 100% of diesel fuel.

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